

APPLICATION FOR UNITED STATES PATENT

HIGH DENSITY ANALOG RECORDING

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HIGH DENSITY ANALOG RECORDING

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5 in this invention.

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. Provisional Patent Application No. 60/193,059, (Attorney Docket No. CALMP024+) entitled HIGH DENSITY STORAGE
BY SEGMENTED ANALOG RECORDING ON PHASE CHANGE DISK filed
10 3/29/2000 which is incorporated herein by reference for all purposes and U. S. Provisional Patent Application No. 60/244,819 , (Attorney Docket No. CALMP029+) entitled ANALOG RECORDING ON PHASE-CHANGE OPTICAL DISKS filed 10/31/2000 which is incorporated herein by reference for all purposes.

FIELD OF THE INVENTION

15 The present invention relates generally to optical data storage. More specifically, high density analog recording is disclosed.

BACKGROUND OF THE INVENTION

Perhaps the most significant breakthrough in the field of optical data storage technology has been the shift from analog to digital recording. Many benefits such as error correction and data compression result from the introduction of digital schemes. It must be recognized, however, that by introducing the techniques of digital recording, delicate features in the recorded patterns of information on the media have been lost. To eliminate the gap between digital and analog schemes and to increase recording capacity, various multi-level recording methods have been investigated.

The tradition in digital storage is to try to record “perfect marks” on the storage medium (disk, tape, etc.). An ideal mark is one that is fully saturated in one or the other state (e.g., amorphous or crystalline), fills the width of the track uniformly, has smooth boundaries, and has the correct length and center position. Writing ideal (or near-ideal) marks entails substantial efforts on the part of the drive/media designer. As higher recording density is required, obtaining ideal or nearly ideal recording marks becomes more difficult. What is needed is an alternative approach to optical recording that will enable higher recording densities to be achieved.

SUMMARY OF THE INVENTION

Accordingly, a recording system combining analog recording with digital processing schemes that preserves the main advantages of digital encoding and offers the potential of increased storage density is disclosed. In one embodiment, a segmented analog recording method divides the media into data blocks with intervening guard bands. A write pulse is selected for each data block that will result in a readout waveform that is distinguishable from other potential readout waveforms. In one embodiment, an analog partial response method is used to write waveforms that produce desired readout waveforms.

10 In one embodiment, it is determined which waveforms the read channel can and should supply given its particular constraints (e.g., spectral content, bandwidth, noise characteristics, restrictions of the peak amplitude, etc.). Once the desired read waveforms have been identified, strategies are developed for recording “patterns” (e.g., amorphous/crystalline regions on phase-change media, magnetic domains on MO media) 15 that can produce the desired waveforms during readout. In one embodiment, a genetic algorithm is used to develop appropriate recording strategies. By employing the heretofore forbidden mark/space patterns at the medium, the proposed analog schemes are capable of delivering higher recording densities. Also, by allowing the system designer to match the read waveforms to channel characteristics, the proposed schemes 20 use the available SNR more efficiently.

It should be appreciated that the present invention can be implemented in numerous ways, including as a process, an apparatus, a system, a device, a method, or a computer readable medium such as a computer readable storage medium or a computer network wherein program instructions are sent over optical or electronic communication
5 links. Several inventive embodiments of the present invention are described below.

In one embodiment, a method of determining a write strategy for recording data on a medium includes defining a set of variable write parameters; generating a plurality of candidate write symbols that specify different values for the variable write parameters; generating a plurality of readout waveforms produced by the plurality of candidate write
10 symbols; analyzing the readout waveforms produced by the marks to determine a set of distinguishable readout waveforms; and selecting selected ones of the plurality of candidate write symbols that correspond to the distinguishable readout waveforms to be included in a set of write symbols that are suitable for mapping to data for the purpose or writing data to the medium.

15 In one embodiment, a recording medium has data blocks written on it wherein the data blocks are written using a set of write symbols determined by defining a set of variable write parameters; generating a plurality of candidate write symbols that specify different values for the variable write parameters; generating a plurality of readout waveforms produced by the plurality of candidate write symbols; analyzing the readout
20 waveforms produced by the marks to determine a set of distinguishable readout waveforms; and selecting selected ones of the plurality of candidate write symbols that correspond to the distinguishable readout waveforms to be included in a set of write

symbols that are suitable for mapping to data for the purpose or writing data to the medium.

In one embodiment, a method of recording data on a recording medium includes mapping the data to a set of write symbols wherein each write symbol represents more than one bit of the data and wherein the set of write symbols is defined by defining a set of variable write parameters; generating a plurality of candidate write symbols that specify different values for the variable write parameters; generating a plurality of readout waveforms produced by the plurality of candidate write symbols; analyzing the readout waveforms to determine a set of distinguishable readout waveforms; and selecting selected ones of the plurality of candidate write symbols that correspond to the distinguishable readout waveforms to be included in the set of write symbols; and writing the data to the medium using the write symbols.

In one embodiment, a method of determining a write strategy for writing data to and reading data from a read/write channel includes defining a set of variable write parameters; generating a plurality of candidate write symbols that specify different values for the variable write parameters; generating a plurality of readout waveforms produced by the plurality of candidate write symbols; analyzing the readout waveforms produced by the marks to determine a set of readout waveforms that match the read/write channel; and selecting selected ones of the plurality of candidate write symbols that correspond to the set of readout waveforms that match the read/write channel to be included in a set of write symbols that are suitable for mapping to data for the purpose or writing data to the medium.

In one embodiment, a recording medium has data written on it wherein the data is written using a set of write symbols determined by: defining a set of variable write parameters; generating a plurality of candidate write symbols that specify different values for the variable write parameters; generating a plurality of readout waveforms produced by the plurality of candidate write symbols; analyzing the readout waveforms produced by the marks to determine a set of readout waveforms that match a read/write channel that includes the recording medium; and selecting selected ones of the plurality of candidate write symbols that correspond to the readout waveforms that match the read/write channel that includes the recording medium to be included in a set of write symbols that are suitable for mapping to data for the purpose or writing data to the medium.

In one embodiment, a method of recording data on a recording medium includes mapping the data to a set of write symbols wherein each write symbol represents more than one bit of the data and wherein the set of write symbols is defined by: defining a set of variable write parameters; generating a plurality of candidate write symbols that specify different values for the variable write parameters; generating a plurality of readout waveforms produced by the plurality of candidate write symbols; analyzing the readout waveforms produced by the marks to determine a set of readout waveforms that match a read/write channel that includes the recording medium; and selecting selected ones of the plurality of candidate write symbols that correspond to the readout waveforms that match the read/write channel that includes the recording medium to be included in the set of write symbols; and writing the data to the medium using the write symbols.

These and other features and advantages of the present invention will be presented in more detail in the following detailed description and the accompanying figures which illustrate by way of example the principles of the invention.

100 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118 119 120 121 122 123 124 125 126 127 128 129 130 131 132 133 134 135 136 137 138 139 140 141 142 143 144 145 146 147 148 149 150 151 152 153 154 155 156 157 158 159 160 161 162 163 164 165 166 167 168 169 170 171 172 173 174 175 176 177 178 179 180 181 182 183 184 185 186 187 188 189 190 191 192 193 194 195 196 197 198 199 200 201 202 203 204 205 206 207 208 209 210 211 212 213 214 215 216 217 218 219 220 221 222 223 224 225 226 227 228 229 230 231 232 233 234 235 236 237 238 239 240 241 242 243 244 245 246 247 248 249 250 251 252 253 254 255 256 257 258 259 260 261 262 263 264 265 266 267 268 269 270 271 272 273 274 275 276 277 278 279 280 281 282 283 284 285 286 287 288 289 290 291 292 293 294 295 296 297 298 299 300 301 302 303 304 305 306 307 308 309 310 311 312 313 314 315 316 317 318 319 320 321 322 323 324 325 326 327 328 329 330 331 332 333 334 335 336 337 338 339 340 341 342 343 344 345 346 347 348 349 350 351 352 353 354 355 356 357 358 359 360 361 362 363 364 365 366 367 368 369 370 371 372 373 374 375 376 377 378 379 380 381 382 383 384 385 386 387 388 389 390 391 392 393 394 395 396 397 398 399 400 401 402 403 404 405 406 407 408 409 410 411 412 413 414 415 416 417 418 419 420 421 422 423 424 425 426 427 428 429 430 431 432 433 434 435 436 437 438 439 440 441 442 443 444 445 446 447 448 449 450 451 452 453 454 455 456 457 458 459 460 461 462 463 464 465 466 467 468 469 470 471 472 473 474 475 476 477 478 479 480 481 482 483 484 485 486 487 488 489 490 491 492 493 494 495 496 497 498 499 500 501 502 503 504 505 506 507 508 509 510 511 512 513 514 515 516 517 518 519 520 521 522 523 524 525 526 527 528 529 530 531 532 533 534 535 536 537 538 539 540 541 542 543 544 545 546 547 548 549 550 551 552 553 554 555 556 557 558 559 560 561 562 563 564 565 566 567 568 569 570 571 572 573 574 575 576 577 578 579 580 581 582 583 584 585 586 587 588 589 590 591 592 593 594 595 596 597 598 599 600 601 602 603 604 605 606 607 608 609 610 611 612 613 614 615 616 617 618 619 620 621 622 623 624 625 626 627 628 629 630 631 632 633 634 635 636 637 638 639 640 641 642 643 644 645 646 647 648 649 650 651 652 653 654 655 656 657 658 659 660 661 662 663 664 665 666 667 668 669 670 671 672 673 674 675 676 677 678 679 680 681 682 683 684 685 686 687 688 689 690 691 692 693 694 695 696 697 698 699 700 701 702 703 704 705 706 707 708 709 710 711 712 713 714 715 716 717 718 719 720 721 722 723 724 725 726 727 728 729 730 731 732 733 734 735 736 737 738 739 740 741 742 743 744 745 746 747 748 749 750 751 752 753 754 755 756 757 758 759 760 761 762 763 764 765 766 767 768 769 770 771 772 773 774 775 776 777 778 779 780 781 782 783 784 785 786 787 788 789 790 791 792 793 794 795 796 797 798 799 800 801 802 803 804 805 806 807 808 809 810 811 812 813 814 815 816 817 818 819 820 821 822 823 824 825 826 827 828 829 830 831 832 833 834 835 836 837 838 839 840 841 842 843 844 845 846 847 848 849 850 851 852 853 854 855 856 857 858 859 860 861 862 863 864 865 866 867 868 869 870 871 872 873 874 875 876 877 878 879 880 881 882 883 884 885 886 887 888 889 890 891 892 893 894 895 896 897 898 899 900 901 902 903 904 905 906 907 908 909 910 911 912 913 914 915 916 917 918 919 920 921 922 923 924 925 926 927 928 929 930 931 932 933 934 935 936 937 938 939 940 941 942 943 944 945 946 947 948 949 950 951 952 953 954 955 956 957 958 959 960 961 962 963 964 965 966 967 968 969 970 971 972 973 974 975 976 977 978 979 980 981 982 983 984 985 986 987 988 989 990 991 992 993 994 995 996 997 998 999 1000

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will be readily understood by the following detailed description in conjunction with the accompanying drawings, wherein like reference numerals designate like structural elements, and in which:

5 Figure 1 is a diagram illustrating a segmented analog recording pattern written to a disc.

Figure 2 is a diagram illustrating different write pulses used in one embodiment.

Figure 3 is a diagram illustrating some of the resulting waveforms selected for inclusion in a pattern table.

10 Figure 4 is a diagram illustrating a sequence of read waveforms obtained by the aforementioned write strategy.

Figure 5 is a diagram illustrating readout waveforms derived from a typical write pattern using four different power levels.

15 Figure 6 is a diagram illustrating the dependence of error-rate on write power variations around its nominal value in one embodiment.

Figures 7A and 7B are diagrams illustrating a pair of waveforms selected to represent the individual channel bits in one embodiment.

DETAILED DESCRIPTION

A detailed description of a preferred embodiment of the invention is provided below. While the invention is described in conjunction with that preferred embodiment, it should be understood that the invention is not limited to any one embodiment. On the contrary, the scope of the invention is limited only by the appended claims and the invention encompasses numerous alternatives, modifications and equivalents. For the purpose of example, numerous specific details are set forth in the following description in order to provide a thorough understanding of the present invention. The present invention may be practiced according to the claims without some or all of these specific details. For the purpose of clarity, technical material that is known in the technical fields related to the invention has not been described in detail so that the present invention is not unnecessarily obscured.

SEGMENTED RECORDING AND MATCHED-FILTER DETECTION

In one embodiment, a segmented recording method is based on recording one byte at a time. A stream of binary data is divided into 8-bit segments, and each segment is written by a specific write waveform. The number of distinct write patterns is 256, and each pattern realizes one of 256 different readout waveforms. During readout, the waveforms obtained from individual segments are compared with waveforms in a pre-stored table, each element of which corresponds to a single byte of information. Using pattern-matching techniques, the recorded information can be retrieved.

Figure 1 is a diagram illustrating a segmented analog recording pattern written to a disc. The length of each segment 102 along the track is divided into two parts. The byte symbol is written in data block 104 while guard band 106 is left undisturbed. The guard band helps avoid inter-symbol interference (ISI) during both readout and recording.

5 By using pattern matching techniques to detect the analog readout waveform, the need for written marks to be oval shape and regular (i.e., ideal marks) is obviated. A possible write pulse 112 for creating the pattern shown in data block 104 is illustrated as well as a resulting readout waveform 114.

In "byte recording" the length of the guard band should be carefully optimized.

10 In one embodiment, the same linear density (without overhead) as DVD-ROM is targeted. With $\lambda = 660$ nm and $NA = 0.6$, the total segment length is set to $2.2 \mu\text{m}$. The length of the guard band is chosen to avoid ISI during reading and thermal cross-talk during writing. In readout, the guard band should be longer than the optical cutoff period of $\lambda/(2 NA) \sim 0.55 \mu\text{m}$. According to thermal simulations, a $0.6 \mu\text{m}$ guard band is also

15 adequate for suppressing thermal interference.

To obtain distinct patterns of read waveform, various patterns of write pulses can be tested and those patterns which are distinguishable from each other selected. In one embodiment, patterns were tested on a DVD-RAM/2.6GB commercial disk. These experiments were performed on a dynamic testbed with $\lambda = 660$ nm and $NA = 0.6$ at a

20 linear track velocity of 6 m/s. Each segment (corresponding to a byte of information) was divided into 22 channels: 16 channels for the data block and 6 channels for the guard

band. The duration of each channel corresponds to 0.1 μ m or 17ns under the above conditions. In one embodiment, 4 of the 16 data block channels were not used during writing to avoid the extension of the recorded marks into the guard band and arbitrary laser power levels were assigned to each of the 12 remaining channels. Three laser power levels produce $3^{12} = 531441$ different write patterns to select from while searching for distinct read patterns. Different numbers of laser power levels may be used in different embodiments.

In one embodiment, a strategy of using simple write patterns was employed in searching for distinct patterns. A variety of waveforms were produced in a systematic way by selecting one, two, or three pulses per segment, each pulse having one of 4 power levels. Alternatively, randomly-selected write power waveforms could be chosen to obtain a large number of arbitrary-looking read waveforms. In general, it is possible to avoid complex algorithms for determining the write patterns given that the choice of write pattern for a given read waveform is not unique, and that a certain amount of write power margin is generally necessary to distinguish the resulting waveforms from each other.

Figure 2 is a diagram illustrating different write pulses used in one embodiment. Each pulse is 2 or 3 channel bits long, and the positions of the pulses vary. Such pulses may generally be produced by available lasers and laser power control interfaces. Pulse power levels P_1 and P_2 were chosen as 9, 10, 12 and 14 mW, respectively, in order to reduce amplitude fluctuations of the read signal.

Numerous write patterns were subsequently used to record amorphous mark patterns of differing shapes. Each read signal was then analyzed to determine its distinguishability from other generated waveforms.

Figure 3 is a diagram illustrating some of the resulting waveforms selected for inclusion in a pattern table. A variety of patterns is seen to emerge. Using one set of distinguishability criteria, the total number of distinguishable waveforms obtained using these simple pulses was 220. A target of 256 waveforms or more, if desired, is attainable if more complex write patterns are used.

Figure 4 is a diagram illustrating a sequence of read waveforms obtained by the aforementioned write strategy. It is clear that each segment has been recorded and retrieved distinctly from its adjacent neighbors.

Figure 5 is a diagram illustrating readout waveforms derived from a typical write pattern using four different power levels. Each trace contains 100 superimposed signals. The observed amplitude deviations are 3.5~3.7%. The 220 distinguishable patterns obtained above remain distinguishable with this level of variability.

Once the patterns are written and read, the distinct readout waveforms must be detected and distinguished. In one embodiment, a detection method software imports the sampled waveform, normalizes the signal amplitude, arranges for synchronization, and separates the signal into individual segments. The cross-correlation coefficients between each readout segment and the patterns in the look-up table are calculated. Since cross-correlation does not effectively distinguish waveforms with similar shapes but different

magnitudes, the DC levels of the readout waveforms are also compared with those of the patterns in the table. When both parameters fall within acceptable ranges, the read pattern is successfully detected.

Figure 6 is a diagram illustrating the dependence of error-rate on write power variations around its nominal value in one embodiment. Although the error rate was below 10^{-3} at the optimum power level, it increased dramatically when the write power decreased by more than 5%. This result is reasonable considering that (i) the waveforms in our table were chosen to have $\pm 10\%$ margin in amplitude against other waveforms and (ii) a 5% reduction of power causes a 10% amplitude reduction for small marks. Precise laser power control is therefore important. Preferably, the allowable amplitude fluctuation is less than 6% and the tolerance of write power variation is 2 – 3%.

To improve the margin of error, the distance between adjacent waveforms may be increased. However, increasing the distance between adjacent waveforms reduces the number of possible readout signals, which results in a lower storage density.

A segmented analog recording method has been described. Relatively simple write pulses with limited (4 level) power variation produces at least 220 distinguishable readout waveforms. In different embodiments either more or fewer readout waveforms may be produced by providing more or less complex allowed write pulses and allowed power variations. The required guard band for each segment, however, limits storage efficiency. Also it would be desirable to develop a scheme that would implement a more simple signal detection scheme than the described matched filter. Accordingly, an

alternative analog recording method using aspects of the PRML signaling scheme has also been developed.

ANALOG PARTIAL RESPONSE METHOD

To implement analog partial response recording, the first step is to identify ideal
5 read waveforms that match the channel characteristics as closely as possible. Because such waveforms are expected to emerge directly from the photodetector(s), they require no further (electronic) equalization, thus eliminating the additional noise introduced by equalization in conventional systems. The spectrum of the ideal readout waveforms can be made to follow the channel's SNR spectrum. This allows a closer approach to the
10 information-theoretic capacity of the media than is possible in conventional systems, where the read waveform is a by-product of a writing strategy that is largely ignorant of the read channel characteristics.

A pair of waveforms are selected for the individual channel bits 1 and 0. Figures 7A and 7B are diagrams illustrating a pair of waveforms selected to represent the
15 individual channel bits in one embodiment. The 0 waveform is an inverted version of the 1 waveform. Preferably, the pair of waveforms match the channel characteristics as closely as possible. Typically each waveform is zero at all multiples of the clock period Δ , except at a finite number of points, where each has a set of well defined non-zero values. For the waveforms illustrated in Figure 7, the non-zero values of the chosen
20 functions are ± 0.75 and ± 1.5 volts, occurring at $t = 2\Delta, 3\Delta$ and 4Δ .

Since the illustrated 1 and 0 waveforms are similar to the equalized output of a PRML channel, Viterbi's algorithm can be used to extract the stored bit-sequences from the readout waveforms.

The clock period Δ is chosen based on the wavelength λ of the laser, the numerical aperture NA of the objective, and the linear velocity V of the disk. For the waveforms illustrated in Figures 7A and 7B, the width of the individual One/Zero waveforms, $\sim 4\Delta$, should be roughly equal to $\lambda/(NA \cdot V)$. In a DVD-RAM system where $\lambda = 650$ nm, $NA = 0.6$, and $V = 6$ m/s, a reasonable choice for the clock period is $\Delta = 45$ ns. In other embodiments, the clock period may be reduced.

The One and Zero waveforms of Figures 7A and 7B have identical spectra (because they differ only by a sign factor). Figures 7C and 7D are diagrams illustrating the normalized amplitude of the Fourier transform of these functions. Figure 7C shows a linear scale and Figure 7D shows a logarithmic scale (decibels). The cutoff is seen to occur at $f\Delta \approx 0.5$, corresponding to $f_c = 2NAV/\lambda$, which is the well-known cutoff frequency of optical storage systems. Above the cutoff, the spectral strength of the waveform is less than -36 dB, which is typically below the noise level and, therefore, acceptable.

During readout, the spectrum of a random bit-sequence will be the same as the Fourier transform of the One/Zero waveform, shown in Figure 7D. Therefore, in the initial design phase, it is preferred that the One/Zero functions are adjusted until their (common) spectrum becomes band-limited and closely resembles the channel's spectrum

of signal-to-noise ratio, $SNR(f)$. In other words, the spectral strength of the read waveforms should be greatest where the channel has the largest SNR , weakest where SNR is small, and negligible beyond the cutoff frequency f_c .

Once the One/Zero waveforms have been selected, a block-length N is chosen for
5 the sequence of channel-bits to be recorded as a single block on the storage medium. For instance, if $N = 20$, one out of $2^{20} = 1,048,576$ patterns will be written to the disk, each expected to yield an individual 20-bit-block waveform upon readout. The next step involves forming all 2^N possible waveforms that one expects to obtain upon reading an N -bit-block. This is done by shifting along the horizontal axis the One/Zero waveforms in
10 multiples of the clock period Δ , then adding the shifted functions in accordance with the particular N -bit sequence under consideration. For the One/Zero waveforms of Figures 7A and 7B, which are 6Δ – long, the total length of the N -bit waveform will be $(N + 5) \Delta$. Figures 8A – 8D are diagrams illustrating a few such waveforms for $N = 20$.

The next step is to develop a writing strategy that would lead to recorded
15 “patterns” on the disk which, upon readout, would yield these ideal waveforms. This can be accomplished in a number of ways, including randomly searching for write strategies that produce desired waveforms or using expert knowledge of the write process to generate candidate write strategies that are likely to produce desired waveforms. In one embodiment, a genetic algorithm is used to find appropriate sequences of laser pulses that
20 will produce each of the 2^N read waveforms.

The sequence of laser pulses are specified by several adjustable parameters. Typically, these parameters include the duration and height of each pulse, the width of a cooling pulse following each heating pulse, and the interval and the laser power level between adjacent pulses. In different embodiments, different adjustable parameters may be used to specify laser pulses. Enough variation in the pulses is provided so that the desired readout waveforms can be produced.

In one embodiment, a genetic algorithm is used to search for appropriate laser pulse sequences. The parameters that define a laser pulse sequence are specified in a table and adjusted. There are 2^N rows in the table, each row containing all the parameters needed to record a single pattern on the medium that corresponds to a specific read waveform. The goal of the search procedure is to find optimum values for each set of such parameters. The search procedure includes the following steps:

Step 1: Select one row from the Table and assign a random set of values to the various write parameters. Record the random pulse sequence and the read the recorded pattern. If desired, the readout signals may be averaged over multiple recordings to reduce noise. Compare the ideal (desired) waveform for the selected row with the actual (averaged) signal that is obtained.

Step 2: Introduce small, random variations (mutations) in each of the parameters of the write sequence. Record the sequence is again (as in Step 1) and compare the resulting read signal with the desired waveform. If the agreement between the two

waveforms improves as a result of a particular mutation, accept that mutation, otherwise reject it (survival of the fittest).

Step 3. Repeat Step 2 until a stable set of parameters is obtained, that is, until further adjustments to the write sequence become ineffectual in improving the read waveform, and all subsequent mutations are rejected. At this point the write sequence
5 should yield a readout signal that is nearly identical to the desired waveform.

Step 4. Repeat the above steps for another row in the Table until all rows are exhausted.

In one embodiment, this process is improved by choosing the initial values of the
10 parameters in accordance with some expert knowledge of the recording process. A purely random strategy may also be used, and such a strategy is expected to converge, albeit somewhat more slowly, under selection pressures to a good writing scheme for each N -bit sequence. Developing the write strategy might require several hours or longer on an automated system, but this procedure need only be performed only once during the
15 development cycle of a given product. When all the adjustable parameters have been fixed at their optimal (or near-optimal) values, the complete lookup table is programmed into a ROM chip and placed in the disk drive.

In one embodiment, a genetic algorithm is somewhat limited to simplify the search procedure. The parameters to be randomly mutated are the power levels of the
20 write pulses. All write pulses are composed of an arbitrary number of the write channel bits. The width of the write channel bit is fixed at $\Delta/2$. The Block size N is 20.

Therefore, the length of each waveform is 20Δ , and the number of the write channel bit corresponding to each waveform is 40. In generating the write pulse sequence, one of these 40 write channel bits is randomly chosen and the power level of the write pulse corresponding to the chosen write channel bit is randomly selected from four
5 predetermined values. The following search process is implemented:

Step 1. The theoretical target waveform is divided into component patterns according to every peak.

Step 2. As an initial write pulse sequence, a set of the unique write pulses is assigned in accordance with the height and width of the peak and valley, respectively, in
10 each component pattern. The unique write pulses are experimentally determined in advance on the basis of expert knowledge.

Step 3. After the first writing was performed, the actual readout waveform is compared with the target waveform.

Step 4. RMS differences by every component pattern is calculated and a search is
15 performed for the component pattern with the largest difference.

Step 5. One write channel bit is randomly chosen from the worst component pattern and its power level is randomly selected from the four predetermined values as a mutation.

Step 6. After writing was performed again, the actual readout waveform is
20 compared with the target waveform.

Step 7. If the difference is reduced, the selected power level of the channel bit replaces that of the previous write pulse sequence. Otherwise, the previous write pulse sequence is maintained.

Step 8. Repeat steps 5 ~ 7 until stabilized.

5 **Step 9.** RMS differences by every component pattern are calculated again and the component pattern with the largest difference is searched.

Step 10. Repeat steps 4~9 until stabilized.

Step 11. The peak or middle melting power levels are randomly changed within $\pm 10\%$,

10 **Step 12.** Repeat steps 4 ~ 11 until stabilized.

In one embodiment, the following alternative search process is used:

Step 1. The theoretical target waveform is divided into peak or valley patterns.

Step 2. To simulate the patterns, a set of unique write pulses is assigned respectively in accordance with the height and width of each peak and valley. The
15 unique write pulses were experimentally determined in advance, on the basis of expert knowledge. This procedure is further described in connection with Figure 9.

Step 3. Rules are assigned. i) The first 2 channels are considered associated with the last 2-channel of a previous waveform. ii) Gaps between the assigned pulses are filled by the erase-pulses. iii) Write pulse assigned to the middle level (=) 0 are

varied in accordance with the adjacent patterns. iv) Long spaces make the following pulse 1 Δ longer.

Step 4. The first writing is performed and the actual readout waveform is compared with the target waveform.

5 **Step 5.** If the difference surpassed the predetermined threshold, the position of each write pulse set is randomly shifted by $\pm \Delta$ or $\pm \Delta/2$.

Step 6. Steps 4 and 5 are repeated.

Step 7. If the difference continues to be above the threshold, the laser power of each write pulse set is randomly shifted by 5%.

10 **Step 8.** Steps 4 to 7 are repeated.

Step 9. If the threshold is not determined in advance, the pulse sequences and the power that realized the lowest difference is selected from all its combinations.

Figures 9A-9D are diagrams of illustrating a decomposition procedure of a target waveform. Figure A is a whole waveform. The waveform is decomposed into 1~10
15 component waves. Figures 9B, 9C and 9D are a classification table of the component waves (bottom) and corresponding write pulse sets having four power levels (top). Hatched bars depict assigned pulses and white bars are neighboring pulses. In one embodiment, the pulses were optimized under the following conditions: $\lambda = 660nm$, NA=0.6, Disk: DVD-R/W. Write/read linear velocity = 5.4 m/s, $\Delta = 50$ nsec. The peak

melting, middle melting, erasing and reading powers levels were 14.7, 11.2, 5.0, and 1.0 mW, respectively.

Other search procedures are used in different embodiments. In general, a search procedure may be optimized according to a specific type of media that is used and
5 variable writing parameters that are available.

Analog optical recording has been described based on the concept of reading
“analog waveforms” from an optical disc that are generated by recorded
amorphous/crystalline patterns. Using a segmented analog recording method with guard
bands, a variety of distinguishable readout waveforms are obtained. In an alternative
10 method using partial response signaling, 0 and 1 waveforms are defined to match the
channel and readout waveforms are formed by shifting and adding the 0 and 1
waveforms. A genetic search algorithm is used to determine write strategies that will
create the desired readout waveforms.

In the description above, for the purpose of example, a phase change optical disc
15 has been referred to as a preferred recording medium. It should be recognized that the
techniques disclosed herein are particularly applicable to phase change optical discs and
that the application of these techniques to optical data storage is an important advance of
that art. In particular, the techniques have been applied to commercial DVD RAM discs
and DVD R/W discs and discs made of materials including AgInSbTe and GeSbTe. In
20 addition, the techniques disclosed herein may be applied to other storage media,
including other optical media such as magneto-optical discs, read only discs, or write

once read many discs, as well as other types of storage media such as magnetic storage media.

Although the foregoing invention has been described in some detail for purposes of clarity of understanding, it will be apparent that certain changes and modifications may be practiced within the scope of the appended claims. It should be noted that there are many alternative ways of implementing both the process and apparatus of the present invention. Accordingly, the present embodiments are to be considered as illustrative and not restrictive, and the invention is not to be limited to the details given herein, but may be modified within the scope and equivalents of the appended claims.

10 WHAT IS CLAIMED IS: